

INK JET PRINTING

M R Keeling

The flexibility and reliability of modern, high-speed ink jet printers offer several advantages over conventional printing. The development of the technology could also lead to valuable spin-offs in fields such as dispensing and spray drying

The term ink jet printing covers a wide range of non-impact techniques, all of which project drops or sprays of ink on to a printing substrate. In all its forms ink jet is basically a computer controlled process which enables continuously variable data to be printed at high speed. Apart from the single jet alphanumeric printers which compete with impact printer techniques, ink jet generally finds its place in areas where its unique characteristics can be employed with advantage over conventional methods. The main characteristics which differen-

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tiate ink jet from most other printing techniques are:

Variable data: The input data can be continuously variable and can range from simple alphanumerics to digitised graphics.

Plain paper: The process prints directly on to the substrate and generally needs no subsequent toning or fusing.

Noncontact: The printer does not at any time make contact with the substrate and, since only the drops of ink are projected on to the surface, printing can be carried out on to any plane, uneven or delicate surface. This makes possible printing on such things as corrugated cardboard, fabrics, tissues, fresh foodstuffs, recessed surfaces, cellophane, etc.

Versatile: The system can be operated with a wide range of specially developed inks to allow printing on to most surfaces. Typically available are edible inks and inks for printing on to metals, plastics, glass and, of course, paper.

Multicolour: Some ink jet printers are capable of printing with a number of coloured inks to form computer controlled patterns. One application is that of multicoloured fabric printing whereby short runs are easily achieved and requirements for warehousing can be significantly reduced.

High speed: The achievable printing speed depends very much on the type of ink jet used but in all cases the data are continuously variable. Typical printing speeds are alphanumerics at 3.5 m s^{-1} , wide width graphics at 1 m s^{-1} and for some applications 10 m s^{-1} . Faster speeds are



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possible but inevitably result in increased costs.

No moving parts: Apart from the Hertz oscillating capillary printers, ink jet printers have no moving parts and therefore are inherently reliable.

In this article I shall consider two main types of printers: *continuous jet*—deflected to print, undeflected to print and unvibrated jet (Hertz)—and *impulse* or drop on demand. A number of other techniques (e.g. electrostatic pull) are also used but as these are a minority they will not be covered.

The techniques used in ink jet printing are applicable to many other fields where the ability to control small volumes of liquid precisely is important. Typically this can include crop spraying, atomisation, spray drying, calibration of drop sizes, etc. Some of these applications are discussed in general terms. The intention of the article is not to provide a detailed theoretical analysis of the various methods but rather to discuss them in broad terms, highlight the problems and identify the markets and products currently available.

Continuous jets deflected to print

Deflected, continuous jet printers are all based on the work on high speed oscillography carried out by Richard Sweet (1964) at Stanford University. A number of variants are available which differ in the way jets are produced, or data are input, etc, but they all operate as shown in figure 1.

A conducting ink is supplied under pressure to an ink gun and forced out through a small nozzle of typically $35\text{--}80 \mu\text{m}$ diameter. As it passes through

the nozzle the liquid is piezoelectrically pulsed (or modulated) and the stream breaks up into a continuous series of drops which are equally spaced and of equal size. Surrounding the jet at the point where the drops separate from the liquid stream is a charge electrode. A voltage is applied between the charge electrode and the drop stream and when a drop breaks off from the stream it therefore carries a charge proportional to the applied voltage at the instant at which it breaks off. By varying the charge electrode voltages at the same rate as drops are produced it is therefore possible to charge every drop to a predetermined level. The drop stream continues its flight and passes between two deflector plates which are maintained at a constant potential, typically $\pm 2.5 \text{ kV}$. In the presence of this field a drop is deflected towards one of the plates by an amount proportional to the charge carried. Drops which are uncharged are undeflected and collected by a gutter to be recycled into the ink gun. Those drops which are charged, and hence deflected, impinge on a substrate travelling at high speed at right angles to the direction of drop deflection.

By varying the charge on individual drops, whatever pattern is required—including alphanumeric characters—may be printed. It is thus possible to use an ink jet system for printing a page of graphics by using a bank of nozzles. A series of drops deflected across a printing web is known as a raster. It is generally accepted that the best quality of printing is achievable using this method of printing although inevitably there are trade-offs

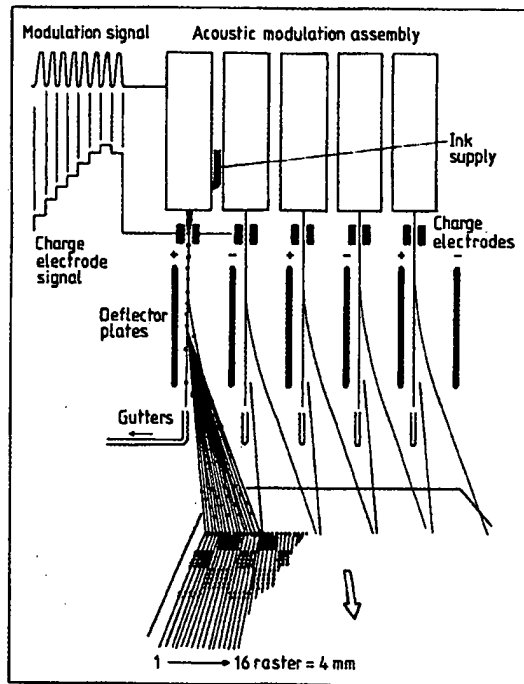


Figure 1 Principle of deflected, continuous jet printers

between speed and resolution. The speed of printing depends primarily on the drop production frequency, the number of drops in a raster and the resolution of printing. Thus faster printing can be achieved, in general, by increasing frequency and decreasing either the number of drops in the raster or the resolution.

Some of the basic equations governing this type of printer are discussed below. The factors affecting jet break-up and charging are applicable to all types of continuous jet printers. Lord Rayleigh (1878, 1882, 1892) showed that if a disturbance was applied to a jet of radius a , the condition for the amplitude of the disturbance to grow and drops to be formed is:

$$\lambda > 2\pi a$$

where λ is the wavelength of the disturbance. If the wavelength of the disturbance were less than the circumference of the jet the amplitude of the disturbance would decay and the jet would break up at some later time due to random background noise. Within this constraint for the formation of drops it has been shown that the growth rate of a disturbance varies with the wave number K as shown in figure 2. The maximum growth rate a_m of a disturbance as a function of fluid parameters was calculated by Weber (1931) to be:

$$a_m = \left[\left(\frac{8\rho a^3}{\sigma} \right)^{1/2} + \frac{6\eta a}{\sigma} \right]^{-1}$$

where ρ represents fluid density, η dynamic viscosity and σ surface tension. If we arrange for the jet to be modulated at the frequency which corresponds to the wave number at which the maximum growth rate occurs, the length L of the jet before drops become detached is given by:

$$L = (v/a_m) \ln(a/\delta)$$

where v represents the velocity of the jet and δ the amplitude of the initial disturbance which needs to be about two orders greater than the background noise. In practice it has been shown that the wavelengths which are useful for obtaining monosized drops lie in the range $3-7D$ (where $D=2a$) and for an inviscid jet the wavelength of the fastest growing wave λ_{opt} occurs when $\lambda_{opt}=4.51D$. Most ink jet printing inks can be considered inviscid and design calculations are frequently based on or near to λ_{opt} . The relationship between the jet velocity v and the frequency of drop production f is given by $v=f\lambda$. Therefore for a fixed wavelength λ_{opt} there can be significant variations between v and f . These two parameters are a compromise between the number of drops necessary to print at a given substrate speed and the velocity of drop which does not result in an unacceptable level of splashing as it hits the substrate.

Before leaving the theory of jets it is useful to note that the amplitude of the disturbance has a significant effect on the shape of the break-up and hence the efficiency of the drop charging. Incorrect modulation levels also result in the formation of satellites (small drops formed between the main and parent drops) which are undesirable unless they rejoin the parent well before reaching the deflector plates.

When a voltage is applied to the charge electrode a charge will be trapped on any drop which detaches from the liquid stream. The U-shaped charge electrode may be considered as two infinite parallel plates and the ink stream as a conducting cylinder. The charge q on the drop for a given charging voltage V is then given by:

$$q = 2\pi\epsilon_0 V \lambda / \ln(4d_c/\pi d_j)$$

where ϵ_0 represents the permittivity of free space, d_c the width of the charging slot and d_j the diameter of the jet. For the full charge to be induced on the drop it is necessary for the risetime of the jet to be sufficiently short. Moreover, because there is a very narrow ligament joining each drop near the point of break-off, the conductivity of the ink must be high to overcome the highly resistive portions of the jet.

The theoretical deflection x of a charged drop passing between the deflector plates is given by:

$$x = \frac{qEZ_d^2}{2mv^2} \left(\frac{2Z_g + Z_d}{Z_d} \right)$$

where E represents the deflection field strength, m the droplet mass, q the droplet charge, v the droplet velocity in the direction of the jet and Z_d and Z_g the

ensity, η dynamic viscosity, we arrange for the jet to have a frequency which corresponds to the maximum growth of the jet before drops are formed.

$\ln(a/\delta)$

velocity of the jet and δ the thickness of the disturbance which needs to be removed rather than the background. It is shown that the wave-number for obtaining monosized drops (where $D = 2a$) and for the growth of the fastest growing disturbance is $\lambda_{opt} = 4.51D$. Most ink jet printers are designed and based on or near to λ_{opt} . The jet velocity v and the frequency f is given by $v = f\lambda$. The length λ_{opt} there can be seen v and f . These two are related between the number of drops at a given substrate on which does not result in splashing as it hits the

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viscosity of free space, d_c jet and d_i the diameter of the drop induced on the drop. The time of the jet to be considered, because there is a very high drop near the point of impact the ink must be high to the portions of the jet. The number of a charged drop or plates is given by:

$$\frac{2Z_g + Z_d}{Z_d}$$

electric field strength, m droplet charge, v the droplet velocity, the jet and Z_d and Z_g the

length of deflector plates and distance between the bottom of the deflector plates and the substrate.

If a single drop is deflected, this equation is modified owing to the aerodynamic drag on the drop. When a number of drops are deflected in close proximity to one another the aerodynamic effects vary from drop to drop depending on whether the drop is travelling through undisturbed air (pioneer drop), or in the wake of another drop and therefore experiencing less drag. Moreover, since all the drops are to be placed at differing points on the substrate they are charged to different levels and therefore will tend to repel one another with a force inversely proportional to the square of the distance between them. If a large number of drops form a raster the number of possible combinations becomes large. To date the theoretical prediction of droplet trajectories has defied accurate solution and raster development is generally carried out on test rigs.

Alphanumeric printers

If a single gun (or nozzle) is used it is possible to print a single or double line of alphanumeric. Printers of this type are relatively simple to produce and the only refinements to the system are the necessity of ensuring that drops are correctly charged (phase control) and that the stream velocity is kept constant (to maintain character height). Methods of carrying out this monitoring/correction are discussed later.

A number of single jet printers are currently available and are produced mainly in the USA, UK, Germany and Japan. All the printers described below incorporate phase control but only the IBM machine corrects for character height. A B Dick (now owned by GEC) produces the single nozzle Videojet alphanumeric printers. These printers have a maximum capability of 1275 characters/s of continuously variable data and employ a resolution of 12-28 points/mm. The intention of these printers is to provide visually acceptable rather than high quality print. There are a large number of these printers worldwide and the major applications are business forms overprinting (addresses, labels, tax details, lotteries, etc),

magazine addressing and product coding (beer canning lines, etc). A wide variety of inks are available which enable printing on to paper, metals and plastics to be carried out.

Domino Printing Sciences Ltd of Cambridge markets a single jet alphanumeric printer which was developed by Cambridge Consultants Ltd. This printer can produce continuously variable alphanumeric characters at a rate in excess of 1500 characters/s with a resolution of 1.0-3.0 points/mm. One interesting feature of this machine is that it is microprocessor controlled which enables it to handle up to six printers from the same electronics and perform sequencing/random number printing. The current market areas are similar to those of the A B Dick printer.

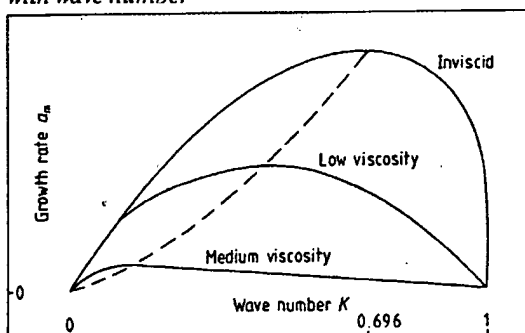
IBM produces the 6640 ink jet document printer which is used in the System 6 word processing package. This printer produces high resolution typewriter quality output and a number of different fonts are available. The specification of this printer is very advanced and it is capable of printing at 92 characters/s (high quality) and 184 characters/s (medium quality). From an ink jet printing standpoint this printer is extremely interesting in that it employs print quality monitoring facilities which make it suitable for unattended operation. Other products employing this method are manufactured by Sharp (Jetprint single jet stand alone terminal, 510 characters/s) and REI (TRACE system for electronic document sorting).

Graphic printers

Cambridge Consultants Limited (CCL) has extended the basic single jet technology into a multi-nozzle graphics system. This is achieved by banking a series of nozzles together into a manifold. Each nozzle has its own charge electrode, deflector plates and gutter and the printer is arranged such that the maximum deflection from one jet butts up to the minimum deflection from its neighbouring jet. Thus by controlling the individual charge electrode signals a graphics output of any width can be obtained. By banking a number of manifolds along the direction of web motion multicolour printing is possible.

Initial development of graphics using this technique was carried out by CCL with the objective of producing an eight colour, large width, fabric printer which would enable instantaneous pattern changes to be made 'on the fly', thus reducing machine downtime and stockholding requirements. A two colour machine was built in prototype form capable of printing at 1 m s^{-1} with a resolution of 4 points/mm but was not taken through to production due to difficulties in locating a suitable manufacturer. Other companies which now have machines built by CCL are Moore Business Forms (forming the basis of its Majic 1000 business forms overprinting system) and the European Thomson Group. Current print resolutions lie between 4-10 points/mm and typical application areas are:

Figure 2 Variation of growth rate of a disturbance with wave number



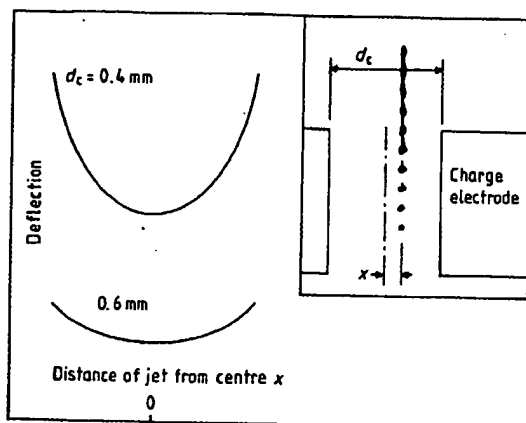


Figure 3 Effect of charge electrode slot width and position of jet on charge received by drop

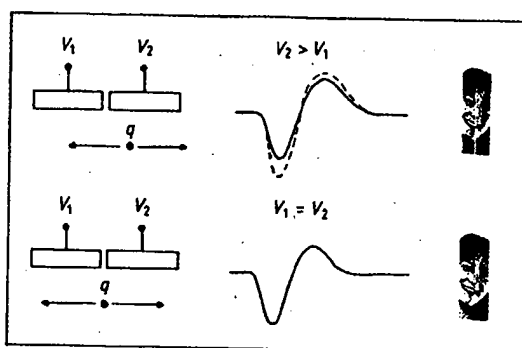


Figure 4 Effect of detector signals on print quality for two-nozzle machine

business forms overprinting; security; high speed facsimile; fabrics, wall and floor covering; line printers; and multicolour confectionery printers.

Print correction techniques

It is appropriate at this point to discuss some of the techniques which make the system practical. The mechanisms of jet formation, drop charging and deflections have already been discussed. However a graphics image formed by a number of adjoining nozzles requires close control of the print if unsightly stripes or unprinted areas are to be avoided. In the following paragraphs consideration is given to the variable factors which can adversely affect quality if allowed to drift and methods of correction are presented.

Typically drops are produced at some frequency in the range 50–150 kHz and the risetime of the ink and the charging voltage electronics must be sufficient for a maximum charge to be induced on the drops. Inevitably the time to charge a drop fully is finite (typically 2–4 μ s) and if the drop detaches from the main stream during this time it will be incorrectly charged. It is therefore important to be

able to vary the timing of the charging pulse so that full voltage has been reached at the instant the drop breaks from the parent stream. There are various ways of achieving this but possibly the simplest is to mount a capacitive detector directly under the charge electrode. A detector is capable of measuring the presence or absence of charge on a drop passing close to it.

Consider a jet which is producing drops at 100 kHz (i.e. a rate of one drop each 10 μ s). If we generate half-width charging pulses of 5 μ s duration at a low voltage which is insufficient to deflect the drops from the gutter on to the substrate we can use the detector to monitor the presence or absence of charge on the drops. If we now move the timing of the half-width pulses in small steps relative to the modulation voltage a point will be found at which the detector will no longer pick up a charge (i.e. drops are uncharged). This point is fixed at the trailing edge of the charging pulse and therefore the timing for full-width printing pulses can easily be determined. Drop phasing is generally carried out whenever the printer is not receiving data. The rate of change of phase is generally quite slow and the causes are: temperature variations (affecting ink viscosity, etc), ink supply pressure drift and long term aging of jet modulators. Other factors which affect the charge received by a drop are the charge electrode slot width and the position of the jet within the slot. Figure 3 shows the effect of these two parameters on drop deflection.

The two important factors which emerge from this and which severely hamper the drop accuracy which can be achieved are as follows:

(1) If all nozzles are identical then the accuracy of drop deflection between adjacent nozzles will be directly related to the equality of the charging slot widths.

(2) For a graphics printer the pitch error of charge electrode slots relative to the nozzle pitch must be kept small and becomes progressively more severe as the charging slot width reduces.

In practice the close tolerances implied above do not become a serious problem except on very wide printers but they do need to be considered when trade-offs between charging voltage, deflector plate EHT and length and flight path lengths are being evaluated.

As mentioned previously it is imperative that the deflections of each jet should butt up against one another so that continuous printing occurs. The deflection of a drop is strongly dependent on the mass of drop and its velocity. For this reason nozzles are calibrated and matched sets are selected which perform almost identically under the printer operating conditions. However, even with matched sets of nozzles the deflection of the drops will vary to some extent due to tolerance on the calibration, mechanical tolerances on components and apparent deflection errors due to misalignment of the jets.

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aligned in the along-the-web direction as this will be discussed shortly. In order to achieve our objective of closely butted jets we need some method of determining where the deflected drops actually go at the substrate so that corrections to the ink pressure or charging voltage can be made. Once again we can use detectors to determine drop positions. A typical detector would be a small piece of metal suitably screened and connected to a millivolt amplifier. Detectors can be arranged near the print point and spaced at the same pitch as the nozzles (and hence deflection). Figure 4 shows typical detector signals and the effect on print quality for a two-nozzle prototype machine.

As the charged drops pass the detectors a signal will be induced on each detector which is dependent on the distance of each from the drop. It is thus possible by comparing signals to determine whether the deflection is high, low or correct. By repeating this across the complete width of the printer or manifold it is possible to vary the system pressure until optimum conditions are reached. Once this has been achieved the remaining errors are due entirely to small mechanical variations between jets, deflector plates, etc, and can be corrected using the detectors and varying the drop charging voltages according to a predetermined pattern.

All multinozzle ink jet technologies suffer from one major problem: the difficulty of making a large number of accurately aligned jets. Developments in the semiconductor industry which enable repeatable sized holes to be etched into silicon plate look hopeful but at present the long flight paths used in CCL's technology have necessitated individually alignable nozzles. Very stable alignment systems have been developed and the small resulting errors can be corrected using the across-the-web system described above and a specially developed along-the-web electronic correction system. The along-the-web systems correct by measuring the misalignment and delaying the data to each charge electrode by an amount dependent on the web speed and the error. The method employed is similar to that

Figure 5 CCL single colour graphics printer

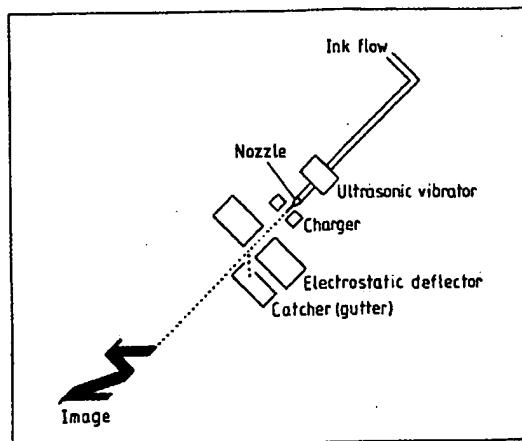
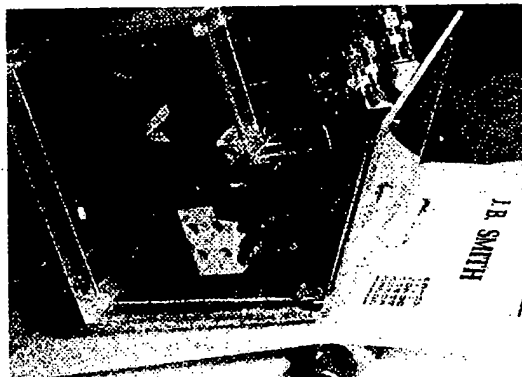


Figure 6 Principle of undeflected, multinozzle jet printers

described for across-the-web correction.

Figure 5 shows a typical single-colour graphics printer built by CCL. The machine is fairly low resolution (3.7 points/mm), prints at up to 1 m s^{-1} and was developed for business forms overprinting. The machine comprises a number of multinozzle modules and by butting modules together, the desired width of printing can be achieved.

Multinozzle jet undeflected to print

In undeflected, multinozzle jet printers liquid is forced through a number of nozzles and is ultrasonically broken up into droplets by vibrating the nozzle plate. At the point where the break-up occurs the jet is surrounded by a charge electrode and drops are charged in a similar manner to the previous type of printer. The main difference is that all unprinted drops are deflected on to the deflector plates and drops required for printing are uncharged and allowed to pass straight ahead on to the printing substrate. Figure 6 shows schematically this type of printer.

There are a number of features which distinguish this type of printer:

- (1) Every printed point across the printed web requires a single nozzle and therefore a 12 cm wide printer with a resolution of 4 points/mm would require an orifice plate with 480 nozzles.
- (2) The accuracy of drop placement is predominantly determined by the alignment of the individual undeflected jets. Fortunately the flight path from nozzle to paper is short (about 12 mm) and acceptable results can be achieved.
- (3) The printer is inherently extremely fast since printing depends only on the drop production rate (as raster scanning is not employed) and the speed at which data can be processed.
- (4) A single modulator is used to break up all the jets and this inevitably results in some lack of control.

The main difficulties associated with this approach are associated with the high packing

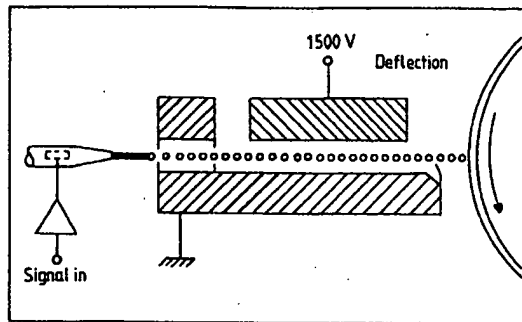


Figure 7 Principle of unvibrated jet printers

density of nozzles. It is not practicable to correct the jet directions electronically and therefore nozzle plates must be fabricated in which all jets issue parallel to one another. Also the on-off switching of jet deflection must be carried out with very closely packed charge electrodes. However, balanced against this is that, when the above problems are overcome, the result is a very fast and electronically simple printer.

The main follower of this technique for graphics is Mead Digital Systems of Dayton, Ohio. IPC now uses Mead machines to print magazine wrappers, which include not only the recipient's name and address but also the postal mark. IBM is certainly pursuing smaller versions using this technique for, most probably, word processor or serial printer applications.

Unvibrated jet (Hertz)

The technology of unvibrated jet printers is attributable to Professor Hertz of Lund Institute of Technology. Professor Hertz has developed a number of printing techniques (Ernbo and Hertz 1969), and the two described here have currently resulted in products. Ink is forced through a small nozzle of typically 10–15 μm diameter and allowed to break up naturally into droplets. Drops are charged by applying a voltage to the ink and having a charge electrode at earth potential. The charge electrode also forms one side of the deflection field, as shown in figure 7.

Drops which are not required for printing are charged and deflected on to the earthed plate which is porous, and the unwanted ink is sucked away. A series of uncharged and hence printed drops impinge on the substrate to be printed. Due to the very small nozzles employed with this technique ink recirculation is not carried out. The main applications of this technology are addressing, facsimile and drum plotters.

Applicon markets a three-colour drum plotter utilising this technology. This plotter will print a 56 cm \times 86 cm sheet in seven minutes with a resolution of 5 points/mm. A modification to the basic printer is to enable the nozzle to oscillate using a Mingograph galvanometer. This type of

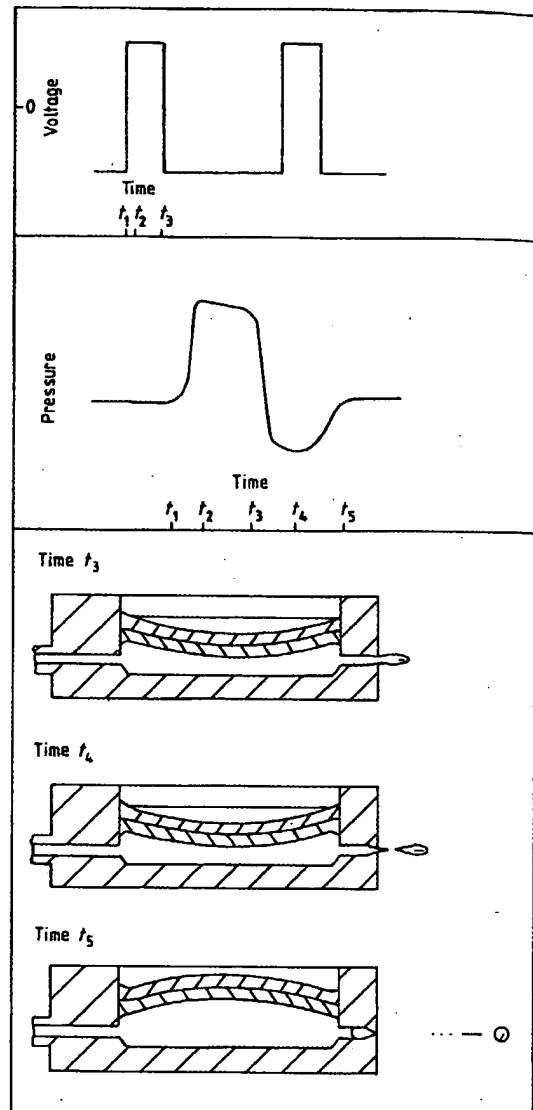
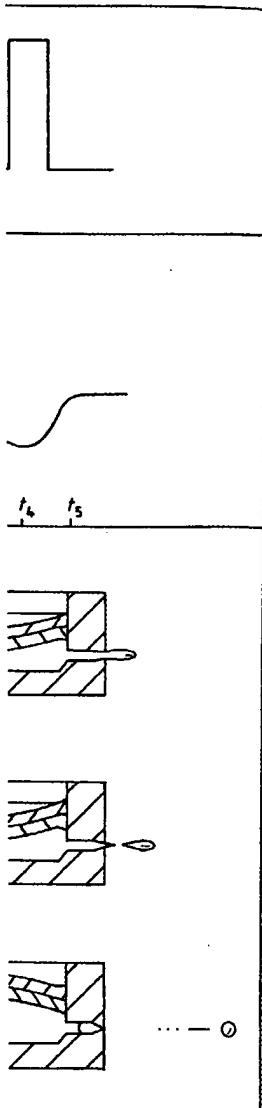


Figure 8 Principle of impulse jet printers

printer is used in the Bell and Howell IJ96 addressing unit. The equipment is a relatively low cost multiline addressing system for office use.

Impulse jets

Impulse jets, commonly called 'drop on demand', are the cheapest and also the slowest type of ink jet printers. Ink is supplied to the head at a very low pressure so that flow from the nozzle is resisted by the meniscus surface tension. Figure 8 shows the operation. When a drop is required a voltage pulse is applied to the piezo crystal and the resulting deflection ejects a drop of ink on to the substrate which is in close proximity to the nozzle. There are two types of impulse jet printers and these are described below.



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In the *undeflected* type a head is made from a number of channels to form nozzles. All the channels leading to the nozzles are linked to a common ink supply and each channel has a piezo element for drop ejection. The vertical height of the character is obtained by pulsing the relevant channel and the horizontal width is achieved either by moving the paper or the printing head. Printers of this type are fairly slow compared with equal quality continuous jet systems but they are extremely cheap. The main problem, which now seems to be overcome, is the conflicting requirement of an ink which does not dry and hence clog the intermittently used nozzles but at the same time dries on the substrate. For this reason most systems are currently used to print on to paper surfaces and some have purge routines which ensure that nozzles are all used at regular intervals. The main market for these machines is as serial printers, batch coders on to labels and facsimile. There are three well established companies in this field and their products are described below.

The Silonics Quietype desk top serial character printer uses seven nozzles and can print at rates of 180 or 210 characters/s. Features provided are character boldening and individual character elongation. There is some doubt over the future of this product. Siemens of West Germany produces the PT80 serial printer which has a 12×9 matrix and can run at up to 270 characters/s. Input uses either the keyboard or ISO-7 bit code. An interesting development of this machine is that it is now being offered as a facsimile printer capable of printing an A4 sheet in three minutes (CCITT Group 2). In 1979 Olympia International launched the 6021 memory typewriter. The characters are formed on a 12×13 or 12×17 matrix and printing is carried out at 130 characters/s.

The *deflected* version of the impulse jet operates in a similar manner to the undeflected printer with the exception that a single nozzle is employed and characters are obtained using a charging ring and deflector plates incorporated adjacent to the nozzle exit. Drops are charged and deflected in a similar manner to continuous jets. The only company which worked on this type of printer was Gould, but this product is no longer available.

Spin-offs from ink jet printing

The interest of most manufacturers is limited primarily to the products they are developing. However, CCL does not suffer from this constraint and has used its ink jet expertise in various other fields. In conclusion some of these other areas are discussed below, but whilst all have been demonstrated to be feasible in the laboratories not all are in production form.

A compound jet has been patented by Professor Hertz and overcomes the inherent problems of all ink jet techniques, that of particulate matter clogging nozzles if adequate filtration is not employed. Generally this is not too much of a

problem as most inks can be made particulate free. However some processes need this facility. A small primary or core jet carries a pure fluid and this is surrounded by a secondary fluid which contains the main ink ingredients. As the primary jet issues from the printer it entrains some of the secondary fluid around its periphery. By altering the height of secondary fluid above the primary nozzle it is possible to vary the amount of secondary fluid entrained. Once the compound jet is formed it can be broken into droplets and used for printing in a similar manner to the other Hertz techniques. The main advantage of this technique is that the primary jet (which could otherwise be prone to clogging) sees only pure fluids and therefore it is possible for the secondary fluid to be formulated using constituents which could not normally be used for printing either because of high viscosity or particle size. Both Professor Hertz and CCL have used the process for printing but just as interesting is its potential for other applications such as encapsulation and printing liquid metals.

The ability to form clouds of monosized droplets is a valuable means of calibrating droplet size distribution measuring instruments, e.g. diffraction or gelatine slide devices. One such instrument produced by CCL utilised 10 and 20 μm diameter nozzles. A constant voltage on the charge electrode caused the droplets to receive equal charge and repel one another to form a cloud. A laser based measuring system was calibrated using this cloud.

By charging and deflecting selected drops it is possible to dispense very low volumes of liquid accurately. Typically, incremental volume steps of $1.5 \times 10^{-13} \text{ m}^3$ can be obtained from a 35 μm nozzle. This could be used for the accurate application of antibiotics or for selected applications of insecticides on to specimens. Using the deflection capability it would be possible to monitor the effects of an insecticide on various selected parts of an insect's anatomy and, probably more important, select an optimum drop size or concentration.

Whilst it is possible to use a number of nozzles as an atomiser an attractive alternative is to form a multitude of liquid ligaments around the periphery of a spinning disc. This has already been done by Drummond (1975) but from the formation of ligaments it is a small step to modulate them, break them into equal sized drops and charge them for, say, electrostatic spray and spray drying applications.

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